Intelligence and neural efficiency: Sex- and task-related effects on EEG coherence

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Running head: IQ and EEG coherence

Abstract

Beneath EEG mapping methods (e.g. Event Related Desynchronization, ERD) which focus on the level of cortical activation the coherence parameter is used to assess the level of functional coupling of brain areas. As there is strong empirical evidence that highly intelligent individuals display a more focused pattern in contrast to a more global pattern of activation during cognitive performance they should be characterized by a lower ERD as well as a lower task related coherence. In a sample of 26 males and 26 females we administered verbal, numerical and figural versions of the Posner task. Twenty-seven-channel scalp EEGs were recorded and Common Average Reference was calculated. Inter- and intrahemispheric task related coherence of EEG activity was computed. Four frequency bands were determined individually for each participant. The results show significant content- and sex related differences in both inter- and intrahemispheric task related coherence for theta and alpha bands. Generally, for all frequency bands total interhemispheric and long distance intrahemispheric coherence produced a consistent pattern of intelligence by sex interaction. While high IQ females display lower coherence as compared to low IQ females for males no significant difference was found. The results suggest sex related IQ differences in use of the brain as determined by EEG coherence.

Keywords: Intelligence; EEG coherence; cortical activation; sex differences; elementary cognitive tasks; Brain function

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Focusing on the aim of finding a biological basis for individual differences in cognitive ability up to now predominantly two lines of research in this field can be outlined: The first is research on the basic processes underlying efficient performance in psychometric intelligence tests (especially speed of information processing). As the main outcome of this scientific area, a consistent negative relationship between reaction times (RT) in elementary cognitive tasks (ECT) and psychometric intelligence (IQ) can be reported (for a review see Neubauer, 1997). This association is usually interpreted in terms of the so called neural efficiency (NE) of the brain as high psychometric intelligence is always associated with a fast execution of elementary cognitive processes (e.g. Vernon, 1993). This may also be of interest in the light of Andersons thoughts about a new and broader concept of intelligence, which expands from the mental test based g construct of general intelligence to a physical based construct n as the neurological concept of g (Anderson, 1995).

For further identification of this hypothesized neural efficiency phenomenon and as a next step towards Anderson's n the physiological correlates of cognitive performance, as they appear directly as functions of the physiological substrate, the brain itself is examined. This is done by means of brain imaging techniques like the measurement of brain's glucose metabolism rate (GMR) using positron emission tomography (PET) or measuring brain's electric activity using electroencephalographic methods (EEG).

Studies using PET have usually found negative relationships between GMR during cognitive performance and psychometric intelligence, i.e. more intelligent persons displayed less glucose metabolism compared to low intelligent participants (Haier et al., 1988, Haier, Siegel, Tang, Abel and Buchsbaum 1992b; Parks et al., 1988). Evidence from EEG studies in favor of a NE hypothesis come from various derivation variants and mathematical techniques on EEG data. Among these are results from evoked potential component (EP) analysis (cf.

Deary and Caryl, 1993; Neubauer, 2000) as well as slow potential topography (Vitouch, Bauer, Gittler, Leodolter and Leodolter, 1997).

To achieve a fine-grained temporal data resolution during performance of ECTs (what would be impossible within the PET paradigm), the so-called "Event-Related Desynchronization" (ERD) method (Pfurtscheller and Aranibar, 1977; Pfurtscheller, Steffan and Maresch, 1988) is used, to allow the study of phasic (i.e. short-lasting) changes of cortical activation. We already have employed this method to investigate spatio-temporal patterns of cortical activation during performance of ECTs, first, with the well known sentence verification test (Neubauer, Freudenthaler and Pfurtscheller, 1995) and second, with Posner's letter matching task (Neubauer, Sange and Pfurtscheller, 1999).

These studies suggest that intellectually bright individuals are obviously less physiologically active during cognitive task performance than average or lowly intelligent individuals. Moreover, brighter individuals can additionally be characterized by a more focused cortical activation pattern during cognitive performance in contrast to a more overall or diffuse activation in the case of lower intelligent persons (Haier et al., 1992b; Jausovec, 1996, 1998; Neubauer, Schrausser and Freudenthaler, 2000).

In a third study (Neubauer, Fink and Schrausser, 2000) we additionally found evidence for a content-specificity on the relationship between cortical activation and intelligence: In ECTs using figural-spatial, numerical and verbal stimulus materials high IQ individuals (especially high IQ females) displayed more distinct spatial patterns of cortical activation when comparing the three contents of the stimulus material; on the other hand, task performance in lower IQ individuals was accompanied by a more unspecific and stronger cortical activation that also spread to other cortical regions that are not specialized for the task. Together with the findings from the first field of research on the basic of intellectual ability (see above) this association supports and widens the concept of the neural efficiency hypothesis which suggests a more efficient use of the brain in high IQ individuals; their brains

consume less energy, presumably because they "use only a limited group of brain circuits and/or fewer neurons" (Haier et al., 1992a, p.134). To develop a meaningful and in consequence working concept of NE, which generally describes intellectual ability on the basis of biological processes, in our view it is necessary to establish not only one or several separately used parameters but rather a profile of variables standing for different physiological properties of the brain. Such a neural efficiency profile (NEP) may consist of variables taken from research on performance in chronometric tests (i.e. RT) on the one hand, as well as variables from brain imaging techniques like PET (GMR) or EEG (i.e. ERD) on the other hand.

To enlarge the NEP beneath EEG mapping methods which focus only on the level of cortical activation a further parameter dealing with the coupling of separate brain areas the so called EEG coherency (Coh) is employed. By means of the EEG coherence analysis anatomical connections (Fein, Raz and Merrin, 1988) as well as functional coupling (Thatcher, Krause and Hrybyk, 1986) of different brain areas can be described (Busk and Galbraith, 1975; Sklar, Hanley and Simmons, 1972). Coherence between two EEG signals (not to be mistaken with EEG correlation, cf. Guevara and Corsi-Cabrera, 1996) is defined as their cross power spectrum normalized for the absolute power values of both signals. It is independent of the absolute level of the EEG amplitudes and may also be considered as a measure of time lag stability between corresponding frequency components of two signals (Nunez et al., 1997). Coherence values are therefore statistical values between Coh = 0 (no coherence) and Coh = 1 (perfect coherence) and so give an indicator for coherent activity of both, phase and power of two EEG signals. "This means that coherence does not give direct information on the true relationship between the two signals, but only on the stability of this relationship with respect to power asymmetry and phase relationship" (Guevara and Corsi-Cabrera, 1996, p.146).

Attempts of relating coherence to cognitive ability produced some promising evidence: First studies of EEG coherence (Thatcher, McAlaster, Lester, Horst and Cantor, 1983; Gasser, Jennen-Steinmetz and Verleger, 1987) have observed an association of lower EEG coherence with higher intelligence, i.e. there is less functional coupling of different brain areas or a more differentiated functioning of the brain. Both studies, however, were conducted with children and await replication in adult samples. Several other studies have demonstrated that coherence increases suggest closer cooperation of the two brain regions actively involved in tasks (Beaumont, Mayers and Rugg, 1978; Wada et al., 1996; Weiss, Rappelsberger and Petsche, 1995 and Weiss and Rappelsberger, 1996).

Recently, a considerable amount of research reports sex differences in several areas of cognitive functioning (e.g. Gur et al., 1995; Haier, 1995; Mansour, Haier and Buchsbaum, 1996; Robinson, 1998; Skandries, Reik and Kunze, 1999; Volf and Razumnikova, 1999; Nyberg, Reza and Herlitz, 2000). Evidence for sex dependent differences in EEG coherence comes from Corsi-Cabrera, Arce, Ramos and Guevara (1997) and Rescher and Rappelsberger (1999), who found different intra- and interhemispheric connectivity of EEG activity in males and females, a finding commonly related to sex differences in certain brain structures (DeCourten-Myers, 1999) or neural density and brain size (Rabinowicz, Dean, Mc Donald-Comber Petot and DeCourten-Myers, 1998; Lynn, 1999; Lynn, Allik and Must, 2000). These studies lend credibility to the existence of sex differences in human brain functioning. It can be conjectured that these sex differences in coherence are predominantly due to these differences in the anatomical and histological structure of the brain (Bishop and Wahlsten, 1997; Nopoulos, Flaum, O'Leary and Andreasen, 1999).

It further can be assumed that there might be sex related IQ differences in EEG coherence, evoked by cognitive activity. This may be quite reasonable, considering the reported sex differences in brains' anatomical construction and functional coupling together with sex specific IQ differences in patterns of cortical activity (Neubauer et al. 2000b).

As the standard coherence method analyzed the EEG for a rather long period (generally no shorter than t = 1 second), this method is hardly suitable for the analysis of short lasting intervals in which functional coupling seems to occur in response to a stimulus. A more recent method, known as Event Related Coherence (ERCoh), has been developed to solve this problem (Rappelsberger, Pfurtscheller and Filz, 1994; Andrew and Pfurtscheller, 1996). The present study employs this ERCoh technique to expand analysis of the data from the Neubauer et al. (2000b) study by means of short lasting task related EEG coherence calculation with respect to sex differences in the brain-IQ relationship. Considering the body of empirical evidence that highly intelligent individuals display a more focused cortical activation pattern in contrast to a more global pattern of activation during cognitive performance in less intelligent participants the former should also be characterized by a lower coherence especially during cognitive performance. However, ERCoh is expected even to differ from ERD findings in order to improve the explanation of NE on the basis of brain processes and hopefully to enlighten additional information for the development of a neural efficiency profile.

Method

Participants

From a pool of N = 167 persons which were recruited through local newspaper advertisements and which were tested with a variety of psychometric tests (see below) we selected n = 60 participants (n_1 = 29 male, n_2 = 31 female) for the EEG study by means of their general mental ability scores (LPS). Because of EEG artifacts 8 persons had to be excluded, the remaining sample included 26 males and 26 females. Based on the general LPS-score (i.e. general intelligence) the entire sample was divided into two groups: The group with lower IQs comprises participants with IQs from 82 to 103 (M = 94.19, SD = 5.24), the higher IQ group included participants from IQ 109 to 131 (M = 118.84, SD = 8.08). Participants' ages ranged from 18 to 49 years (M = 29.06; SD = 7.26). All participants were right-handed

(as determined by self-report) and without any obvious signs of medical or psychological diseases. All participants in the EEG sessions were paid for their participation.

Psychometric tests

For the assessment of intelligence a well-known German intelligence test, the "Leistungs-Prüf-System" (LPS) by Horn (1962) was administered. The LPS provides a measure for general mental ability and scores for specific intellectual abilities. It is partially based upon Thurstone's (1938) primary mental abilities and consists of six subscales (14 subtests) providing scores for (1) general education and orthographical knowledge, (2) recognizing regularities, reasoning, logical thinking, recognizing rules, (3) word fluency, (4) technical ability or giftedness, mental rotation of symbols, spatial imagination involving symbol comparison, (5) visual memory capacity, closure and guessing ability, and (6) perceptual speed. As the LPS did not include a test requiring figural-spatial components we additionally administered the figural subtest of the "Intelligenz-Struktur-Analyse" (ISA, Blum et al., 1998) to obtain a more comprehensive measure of the participants' visuo-spatial abilities.

In order to control for other psychological traits which might be correlated with intelligence and which might influence physiological measures we administered several other psychometric tests: Concentration ability was measured by means of the "Frankfurter-Aufmerksamkeits-Inventar" (FAIR; Moosbrugger and Oehlschlägel, 1995) and creativity by means of the "Verbaler Kreativitätstest" (VKT; Schoppe, 1975). In addition, we assessed the participants personality traits according to the "big five" model of personality (i.e. extraversion, agreeableness, conscientiousness, neuroticism, openness to experience). For this purpose the NEO-FFI by Costa and McCrae (translated into German by Borkenau and Ostendorf, 1993) was administered. To obtain a measure for the temporary mood of the participants in the EEG session (e.g. activation, anger, anxiety, self-confidence, excitement,

sensitiveness, etc.) the "Eigenschaftswörter-Liste" (EWL) by Janke and Debus (1978), a self-report inventory consisting of 15 subscales, was used.

Elementary Cognitive Tasks

Three modified versions of Posner's classical letter matching task (Posner and Mitchell, 1967) were used, employing verbal, numerical and figural-spatial stimulus material. The participants were simultaneously shown pairs of stimuli on a computer screen which were either of identical or of a different name. Originally, ECTs consisting of verbal (i.e. letters), numerical (i.e. arabic and "domino" numbers) and figural-spatial (i.e. arrows) stimuli were used (cf. Neubauer et al., 2000b).

In the verbal matching test the upper and lower case letters "A, B, E, R, a, b, e, r" were used as stimuli. Participants task was to judge whether the presented letters are of identical name or not, i.e. the answer "YES" was required to stimuli of the type "BB", "Ee", or "rr ", the opposite answer "NO" was required to stimuli of the type "AE", "Ba" or "ar".

In the numerical condition arabic numbers and "domino" numbers were used as stimuli (2, 3, 4, 5, , , ,) which were again either "name" identical (e.g."33", "4 " or " "), and had to be responded by "YES" or "name" different (e.g. "24", "3 " or " "), requiring the opposite answer "NO". For the figural-spatial material we decided to present pairs of arrows which were rotated clockwise congruently (e.g. "", " " or " ") as "semantically" identical stimuli or were rotated clockwise incongruently (e.g. "", " " or "") as "semantically" different stimuli, respectively. The participants were instructed to judge and the response "YES" or "NO" whether the presented arrows are the same or not referring to their semantically content, congruent or incongruent. In each experimental condition (i.e. verbal, numerical and figural) 16 practice items and 80 test items were presented. Instead of the original version of Posner's letter matching paradigm for which additionally the Physical Identity (PI) of the stimuli has to be judged we decided to use only the more complex Name Identity (NI) condition given that for a corroboration of the neural

efficiency hypothesis – as shown in the Neubauer et al. (1999) study – obviously a certain level of task complexity (as in the NI condition) is required. At the beginning of each trial a visual fixation stimulus ("+") was presented for 4000 ms on the computer monitor, followed by an auditory warning signal (1000 Hz tone for 100 ms, see Fig. 1). Immediately after the warning stimulus the test stimulus (i.e. the pair of letters) was presented and the participant had to respond to the stimulus by pressing either the "YES"-buttons or the "NO"-buttons. Each response was followed by an intertrial interval of 3150 ms. Instructions stressed speed and accuracy.

Apparatus /EEG Recording

For the presentation of the elementary cognitive tasks (see above) a PC with an external response-console consisting of two horizontally arranged buttons for the "YES" responses and two horizontally arranged buttons for the "NO" responses was used. In order to avoid a confounding effect with hemispheric differences, participants were instructed to response simultaneously with their index fingers in case that a "YES"-response is required and with their thumbs in case that the opposite answer "NO" is required. Stimulation process was realized by means of the G.TEC visual and acoustic stimulation unit and paradigm parser system, G.TEC medical and electrical engineering, Austria.

The EEG was measured by means of gold electrodes (9 mm diameter) located in an "electrode cap" in the following 27 positions, respectively: F_z, F_3, F_4, F_7, F_8, F_{C1}, F_{C2}, F_{C5}, F_{C6}, C_z, C_3, C_4, T_3, T_4, C_{P1}, C_{P2}, C_{P5}, C_{P6}, P_z, P_3, P_4, P_{O1}, P_{O2}, T_5, T_6, O_1, O_2 (according to the international 10-20 system). A ground electrode was located between F_z and C_z. The EEG was monopolarly recorded against nose. For the elimination of artifactual trials caused by eye movements, the electrooculogram (EOG) was measured by means of two gold electrodes: One electrode was placed above the right eye, 1 cm in cranial and 1.5 cm in medial direction; the other electrode was positioned below the right eye, 1 cm in caudal and 1.5 cm in lateral direction. This diagonal placement of the EOG should allow an economic assessment of

horizontal and vertical eye movements. Electrode impedances were kept below 5 kΩ for the EEG and below 10 kΩ for the EOG. All signals were amplified by means of a B.E.S.T amplifier system with low and high cut filters set at 0.3 s and 75 Hz. EEG data were digitized at a sampling rate of 128 Hz.

Selection of individually adjusted frequency bands

Frequency windows for the analyzed bands were determined individually for each participant by using the highest amplitude (peak) in the alpha band as an individual anchor point to identify the dominant EEG frequency (see Klimesch, 1999). The frequency of the dominant peak (IAF) is determined through visual inspection of the EEG spectra with most respect to the P_z channel (n = 4 raters, Cronbach $\propto$ = .99). So, four different frequency windows with a bandwidth of 2 Hz each can be defined: (1) theta band (Th = [IAF – 6 Hz] to [IAF – 4 Hz]), (2) lower-1 alpha band (L1 = [IAF – 4 Hz] to [IAF – 2 Hz]), (3) lower-2 alpha band (L2 = [IAF – 2 Hz] to IAF) and (4) upper alpha band (U = IAF to [IAF + 2 Hz]). The mean frequency values for these individually defined bands were 4.69 to 6.69 Hz for the theta band, 6.70 to 8.69 Hz for the lower-1 alpha band, 8.70 to 10.69 Hz for the lower-2 alpha band and 10.70 to 12.69 Hz for the upper alpha band. Within these individually determined frequency bands coherence calculation took place.

Coherence calculation

Coherence (Coh) at each given frequency (f) is defined by $Coh(f)^2 = |Sxy(f)|^2 / [Sxx(f) * Syy(f)]$ where Sxy(f) is the cross-power spectral density and Sxx(f) and Syy(f) are the respective auto power spectral densities. As it is suggested that the coherence values can be seriously influenced by the use of one common reference electrode (nose), for activity at this reference contributes to two signals of the coherence analysis (i.e. Fein et al., 1988; Essl and Rappelsberger, 1998), to reduce these effects, the recorded EEG data were converted to Common Average Reference using the source derivation (Laplace) method. So, this reference-independent method should cancel the influence effect of a common reference

electrode as now all 27 leads are involved serving as new calculated common reference position.

After the Laplacian procedure coherences were calculated between 7 interhemispheric and 14 intrahemispheric electrode pairs (7 left sided and 7 right sided) in the following 21 positions: For the interhemispheric coherence long distance pairs were calculated between F_7-F_8, T_3-T_4 and T_5-T_6, short distance pairs were calculated between F_3-F_4, C_3-C_4, P_3-P_4 and O_1-O_2. Intrahemispheric pairs were defined as F_4-C_4, F_8-T_4, C_4-P_4, T_4-T_6 and P_4-O_2 for short distance right hemispheric, F_3-C_3, F_7-T_3, C_3-P_3, T_3-T_5 and P_3-O_1 for short distance left sided, F_4-O_2 and F_8-T_6 for long distance right sided and finally F_3-O_1 and F_7-T_5 for long distance left hemispheric. Fourier transformation and coherence calculations were done using the EPS-EEG Processing Software Package for Windows-NT, institute of biomedical engineering, University of Technology Graz, Austria. As depicted in Fig. 1, each EEG trial started 4000 ms before the presentation of an auditory warning stimulus. As period for the task related coherence analysis (ERCoh) served a 125 ms time interval starting 250 to125 ms before participant's response, the so-called pre-reaction interval (PRI).

Averaged reactivity for long and short distance interhemispheric as well as for long and short distance intrahemispheric ERCoh (right and left separately) for each individual determined frequency band was calculated. As coherence is an extension of Pearson's correlation coefficient displaying similar curve characteristics before statistical analysis Fisher's Z-transformation ($Zcoh = 1/2 * \log [1 + Coh / 1 – Coh]$) was applied in order to enforce normality.

Procedure

After the mounting procedure EEG was recorded in a 5 minute resting state with eyes closed. After the resting period subsequently the participant started to work on the matching tests described above. The matching tests were presented in two blocks. The first block consisting of 16 items allowed the participant to practice the task and enabled the

experimentator to check whether the participant understood the instructions correctly. During the second block of 80 items EEG was recorded. The order of trials within the letter matching test was pseudo-randomized. The participants were repeatedly instructed to avoid eye and body movements during the EEG recording as far as possible. After the matching tests a second 5 minute EEG at rest with eyes open was recorded.

Between the presentations of the three matching tasks (i.e. verbal, numerical and figural-spatial variant) short breaks of 3 minutes were allowed. Each experimental test condition took about 20 to 25 minutes per participant resulting in a total time of about 1 to 1¼ hours.

Results

To determine possible Intelligence group (IQ) by gender (sex) by content differences with respect to ERCoh in the PRI interval of the matching test the averaged Z-transformed coherence scores (Zcoh) for long and short distance interhemispheric (InterL and InterS, respectively) as well as for long and short distance intrahemispheric pairs (right IntraLr, IntraSr and left IntraLl IntraSl) for the individual theta, lower-1 alpha, lower-2 alpha and upper alpha band were analyzed by means of three-way analyses of variance (ANOVAs) with task content (figural, numerical, verbal) as within subjects variable and IQ and sex as between subjects variables. In case of violation of sphericity assumptions df were corrected by means of Greenhouse-Geisser Epsilon. Table 1 shows means and standard deviations (SD) for Zcoh for frequency bands by IQ and sex as well as content. It should be noted that the IQ groups did not differ significantly with respect to the personality traits extraversion, neuroticism, openness to experience, agreeableness and conscientiousness (i.e. the "Big Five") and with respect to the EWL-scores. For detailed descriptive statistics of all psychometric test variables (LPS, NEOFFI, FAIR) and median RTs in the letter matching tests see Neubauer et al. (2000b).

First of all, as one of the main outcomes all the interhemispheric coherence scores for all frequency bands with the only exception to the short distance coherency in the upper alpha band did produce a significant IQ by sex interaction (cf. Table 2). In all cases long as well as short distance coherence differences were found in similar patterns which were that low IQ females display a higher coherence score than high IQ females while for males this is of reversed order and far less pronounced (cf. Table 1). In fact, post hoc comparisons by means of Newman-Keuls tests revealed significant coherence differences only for women (with exception to the upper alpha band), while Zcoh differences for men failed to reach significance.

Lets have a look at the detailed results: For the theta band's InterL coherence score, (F [1, 48] = 10.55, $p < .01$) males show a much lower IQ groups difference (IQ low 0.14 vs. IQ high 0.25, n.s.) than females, with this difference going in the opposite direction (IQ low = 0.34 vs. IQ high = 0.17, $p < .05$), brighter women display a much lower ERCoh score compared to low IQ women, which show the highest score (Zcoh = 0.34) for the long distance interhemispheric theta band coherences. The same patterns can be observed for the InterS coherence scores in the theta band (F [1, 48] = 10.12, $p < .01$). Again, men show lower coherence differences in the IQ groups (IQ low = 0.40 vs. IQ high = 0.54, n.s.) compared to women's reversed order findings (IQ low = 0.62 vs. IQ high = 0.43, $p < .05$).

Similar results as for the theta band described above emerged for the two Lower alpha bands. Both, the lower-1 alpha's InterL ERCoh (F [1, 48] = 7.43, $p < .01$) and InterS ERCoh (F [1, 48] = 6.14, $p < .05$) as well as lower-2 alpha's InterL ERCoh (F [1, 48] = 5.94, $p < .05$) and lower-2 alpha's InterS ERCoh scores (F [1, 48] = 4.48, $p < .05$) appeared consistently in the same pattern of interaction (cf. Table 2).

Finally for the upper alpha band we found the same arrangement of Zcoh means as for theta and lower alpha bands. Here, only interhemispheric long distance task related coherence was significant (F [1, 48] = 4.27, $p < .05$), but even though InterS ERCoh failed to reach

significance it displays the same pattern of coherence (males [IQ low: 0.25 < IQ high: 0.27] vs. females [IQ low: 0.36 > IQ high: 0.29]). Again, for interhemispheric coherence scores over all frequency bands (from the theta to the upper alpha band) women display a significance coherence difference between low intelligent and highly intelligent individuals, while for males no clear and in terms of statistical tests tenable differences can be observed.

Further consistent findings resulted for intrahemispheric task related coherence: Interestingly, only long distance coherence scores were found to be significant: To begin with the theta and lower-1 alpha band, here both, right (F [1, 48] = 10.31, $p < .01$; F [1, 48] = 5.04, $p < .05$, respectively) and left (F [1, 48] = 9.56, $p < .01$; F [1, 48] = 6.59, $p < .05$, respectively) intrahemispheric long distance coherences reached significance. Looking at the lower-2 and upper alpha bands it emerges that just one side's coherence reaches significance at a time: IntraLl ERCoh scores (left hemisphere) produced a significant interaction for the lower-2 alpha band (F [1, 48] = 4.08, $p < .05$) and IntraLr coherence (right hemisphere) becomes significant in the upper alpha band (F [1, 48] = 4.72, $p < .05$).

In all cases we found the same patterns of interaction as reported above. Alike the interhemispheric task related coherence score for the long distance intrahemispheric score low IQ women are characterized by a much higher coherence compared to brighter women (cf. Table 1). In contrast to women's results as shown by means of Newman-Keuls' post hoc comparisons men are again characterized by non significant differences between IQ groups' ERCoh score.

A consistent pattern of significant IQ by sex interaction was found for (almost) every frequency band's long and short distance interhemispheric and long distance intrahemispheric task related coherence score. While males show no significant ERCoh differences between IQ groups, females display significant lower ERCoh scores in the high IQ group compared to females' low IQ group. This interaction is especially pronounced for the theta and lower-1 alpha bands.

Dealing with sex as main effect, first of all neither for theta bands interhemispheric nor for theta bands intrahemispheric task related coherence a significant effects could be observed. Concerning InterL ERCoh we found the main effects sex significant for the lower-1 alpha band only, F (1, 48) = 4.11, p < .05, whereas the short distance score produced a tendency effect: In this frequency band men are characterized by a lower InterL task related coherence compared to women (Zcoh = 0.12 vs. 0.19, respectively). In contrast to the lower-1 alpha band are findings for the lower-2 alpha and the upper alpha band. Here only the short distance coherence score produced a significant main effect for sex (F [1, 48] = 5.76, p < .05 for the lower-2 alpha band and F [1, 48] = 4.85, p < .05 for the upper alpha band). In both bands again men display a lower ERCoh compared to women, here not for the long distance scores, as found for the lower-1 alpha band but for the short distance coherence scores (Zcoh = 0.30 vs. 0.38, respectively for the lower-2 alpha band and Zcoh = 0.26 vs. 0.32, respectively for the upper alpha band).

Dealing with intrahemispheric task related coherence this direction of difference, namely men showing a lower coherence value compared to women still holds true for lower-1 alpha band's IntraLr (F [1, 48] = 5.08, p < .05; Zcoh = 0.26 vs. 0.37, respectively). Interestingly, for lower-2- and upper alpha's intrahemispheric short distance scores a reversal of this direction of coherence difference was found: To begin with the lower-2 alpha band, long distance ERCoh was significant for the left hemisphere (F [1, 48] = 4.44, p < .05), short distance ERCoh was significant for the right hemisphere (F [1, 48] = 13.20, p < .01). While long distance coherence performs just as reported above with men displaying lower coherence compared to women (Zcoh = 0.22 vs. 0.29, respectively) this significant difference of coherence is reversed for the short distance right hemispheric score: Here coherence is higher for men than for women (Zcoh = 0.35 vs. 0.27, respectively). The same was found for the upper alpha band: Again, as reported for the lower-2 alpha band, the IntraSr score was

significant (F [1, 48] = 13.83, p < .01) and again task related coherence is higher for men than for women (Zcoh = 0.33 vs. 0.25, respectively).

This similar characteristic of the 2 alpha bands (lower-2 alpha and upper alpha) which obviously differs from that of the lower-1 alpha and theta band may propose a combination of theta band and lower-1 alpha bands on the one hand and lower-2 and upper alpha on the other hand. To test for this, we computed an exploratory factor analysis on the basis of average coherence scores for inter- and intrahemispheric pairs for the three content conditions and for the four frequency bands, resulting in 2 * 3 * 4 = 24 coherence scores. This suggests 3 components extracted by means of the Kaiser criterion (λ_1 = 16.02, λ_2 = 3.78, λ_3 = 1.24) with variance explanation of 87.68%. Performing an enforced 3-component solution with orthogonal rotation (VARIMAX) the first component loadings appear to be mainly interhemispheric scores (λ_{1rot} = 8.92 with 37.16% variance explained) while the second and third component loadings consist of mainly intrahemispheric scores. Component 2 may be interpreted as intrahemispheric "high bandwidth" factor with most of the lower-2 and upper alpha loadings (λ_{2rot} = 6.08 with 25.35% variance explained) while component 3 would allow a intrahemispheric "low bandwidth" interpretation with most of the lower-1 alpha and theta band loadings (λ_{3rot} = 6.04 with 25.18% variance explained).

Finally, when we focus on the within subjects factor of task content several comparisons reached significance: Starting again with interhemispheric coherence scores we found that only the theta band and the lower-1 alpha band did produce a significant content effect (theta band's InterL, F [1.78, 85.46] = 5.08, p < .05; theta band's InterS, F [1.58, 75.62] = 5.75, p < .01; lower-1 alpha band's InterL, F [1.77, 85.03] = 4.15, p < .05; lower-1 alpha band's InterS, F [1.62, 77.75] = 4.70, p < .05), the lower-2 as well as the upper alpha failed to reach significance. In all cases the figural condition produced the lowest ERCoh score compared to the numerical and verbal conditions, which were of almost equal level (see Table 1). Newman-Keuls posttests reveal significant coherence differences for the theta band

between the figural and numerical condition (InterL, p < .05; InterS, p < .01) as well as between the figural and verbal condition (InterL, p < .05; InterS, p < .01) and in the lower-1 alpha band between the figural and numerical condition (InterS, p < .05) as well as the figural and verbal condition (InterL, p < .05; InterS, p < .05).

In sharp contrast to findings for the Intelligence by sex interactions and even the sex main effect's results (see above) for intrahemispheric ERCoh content produced significant effects merely for short distance scores limited to the lower alpha bands. For the lower-1 alpha band both, right as well as left side's short intrahemispheric task related coherence was significant (F [1.62, 77.94] = 9.48, p < .01; F [1.72, 82.74] = 4.24, p < .05, respectively) whereas for the lower-2 alpha frequency band only (right hemispheric) IntraSr score produced a significant effect of content (F [1.70, 81.41] = 5.43, p < .01). In contrast to interhemispheric findings here highest scores emerged for the figural condition in comparison to the numerical and verbal condition. Newman-Keuls test reveal significant coherence differences in the lower-1 alpha band between the figural and numerical condition (IntraSr, p < .01) as well as the figural and verbal condition (IntraSr, p < .01; IntraSl, p < .05) and in the upper alpha band between the figural and numerical condition (p < .01) as well as the figural and verbal condition (p < .05). Summing up, the figural condition stands in clear contrast to the two other conditions (the numerical and verbal tasks). This could be due to either different cognitive mechanisms responsible for solving verbal versus nonverbal stimulus material or simply to the higher figural task's complexity with almost the same level of complexity for the verbal and numerical conditions. An ANOVA on RTs produced a significant main effect for content (F [2, 94] = 482.62, p < .001), post hoc comparisons revealed no significant differences in reaction times between the numerical and the verbal condition (695 vs. 703 ms, respectively) but both versions differed significantly from the figural test condition (1279 ms, p < .01).

Apart from the main effect for content on the coherence measures we found only some accidentally significant interactions of content with other variables, which are not reported here.

Discussion

To investigate the properties and the possible suitability of EEG coherence analysis as additional parameter besides EEG Power or ERD techniques to indicate neural efficiency was the main purpose of this study. In contrast to the measurement of an absolute level of cortical activation (i.e. ERD) EEG coherence indicates functional coupling of different brain areas. In our case a special form of coherence the so called event- or task related coherence (ERCoh) was chosen to test very short lasting activation intervals before participants' reaction to a certain elementary cognitive task. With respect to the aim to develop a parameter system or better a profile to indicate and measure neural efficiency on the bases of basic physiological processes and even as an improvement of the concept of general intelligence g to Anderson's neurological concept n it seemed to be a quite reasonable to take this method for the next step towards this scientific intention. On the basis of the assumption that high IQ subjects use their brains more efficiently (indicated by a stronger spatial focusing of cortical activity) we expected a higher task related coherence for low IQ individuals than for high IQ individuals. Findings concerning gender related coherence differences caused by sexual dimorphism of the brain's structure and physiological properties even suggested the expectation of possible IQ by sex interactions.

Summing up, three predominant results can be reported. To begin with the most interesting outcome a consistent and specific intelligence by sex interaction was observed for event related coherence in the pre reaction interval (PRI). Covering all four frequency bands, from theta to upper alpha, for long and short distance interhemispheric as well as for short distance intrahemispheric (left and right sided) coherence scores the same pattern of interaction arises: Women are characterized by a higher ERCoh for the low intelligence group

compared to the high intelligence group. This finding is in accordance with our expectations concerning coherence difference between intelligence groups as discussed within the neural efficiency hypotheses: High IQ individuals show a lower and more focused pattern of activation. This higher focusation or in other words lower overall activation goes along with lower functional coupling of brain areas especially for longer distances. Here, this assumption can be corroborated for females only. Male individuals display no such coherence difference. The question why coherence seems only sensitive for females in terms of cognitive processes, intelligence and neural efficiency may partly be answered referring to human brains sexual dimorphism.

Before discussing this quite interesting point, let's take a look at the second finding which deals with sex differences in event related coherence which were limited merely to the lower-1, lower-2 and upper alpha band. Different findings of lower-1 in contrast to lower-2 and upper alpha may propose a separation in two groups of frequency bandwidths, namely a "low" band on the one hand and a "high" band on the other hand. Indeed, results of exploratory factor analysis support this heuristic assumption as 2 components, a first with theta and lower-1 alpha loadings, a second with lower-2 and upper alpha loadings could be extracted. As observed for the lower-1 alpha band mainly long distance interhemispheric coherences were significant in contrast to that lower-2 as well as the upper alpha produce predominantly significant short distance inter- and intrahemispheric sex differences. As far as the female group is concerned they display (a) a higher long distance ERCoh for the lower-1 alpha band as well as (b) a higher interhemispheric short distance coupling for high frequency bandwidth (lower-2 and upper alpha). This stronger interhemispheric coherence level indicating a lower lateralization for women in contrast to men's higher lateralization and lower functional coupling of the hemispheres has found thorough confirmation in contemporary brain research (Fein et al., 1988; Thatcher et al., 1986; Sklar et al., 1972; Busk and Galbraith, 1975). Likewise the finding that men display a higher right intrahemispheric

coherence for short distances, due to stronger lateralization of the right hemisphere (being responsible for non verbal, spatial cognitive processes) is in accordance with recent findings (Lacroix et al., 1996; Corsi-Cabrera et al., 1997).

For this sexual dimorphism in coupling function of brain areas several structural properties of the brain seem to be responsible. Known fact is a generally heavier brain for males mainly caused by a higher neuronal density (DeCourten-Myers, 1998; Lynn, 1999). On the opposite women are characterized by a higher amount of glia cells, an overall smaller and lighter brain and a lower number of neurons as well. This lack of neurons probably implies higher number of neural processes in females cortex (Rabinowicz et al. 1998; Lynn et al., 2000) which is partly corroborated with findings of a higher resting power in females EEG. As further anatomic dimorphism a difference in size and shape of the splenum of the corpus callosum, was assumed. According recent findings, however, this belief that women have a larger splenum than men seems untenable (Bishop and Wahlstein, 1997). Maybe not the size of the linkage area of the two hemispheres is of importance but the quality of the neurons building this connection. If there is a larger amount of neurons between the two hemispheres, as observed for men, a more unspecific and inaccurate flow of information could be the effect. On the contrary with a smaller number of neurons, as it is for females, which are of a higher level in activation, a far more specific and accurate electrochemical information flow may be archived, which results in a higher degree coupling and as a consequent effect in a higher level of EEG coherence.

In this context the third outcome, the content specific coherence effect is of interest: Down the line figural condition's ERCoh was in contrast to numerical and verbal conditions' ERCoh which were of almost the same level of coherence. This holds true for the theta band and the lower-1 alpha band as well as for the lower-2 alpha band which on its part stands in a certain contrast to the two lower group frequency bands. In the low bands (theta and lower-1 alpha) several long and short distance coherences were higher for the verbal and numerical

than for the figural condition. This circumstance could be explained with the higher grade of complexity of the figural ECT. A more complex task demands a higher activation of relevant brain areas which consequently causes a lower level of functional coupling. Unlike theta and lower-1 alpha a different pattern was found for the lower-2 alpha band: Here exclusively right intrahemispheric short distance coherences were affected. For the figural task a higher coupling of neighboring cortex areas was observed than for the numerical or verbal ECT. Again this could be explained with the higher complexity of the task on the one hand, but also with some content based peculiarity of information processing resulting in a higher right intrahemispheric coupling for the figural task on the other hand. As the figural ECT implies the effort of mental rotation, basically located within the right hemisphere together with the finding of men having stronger right hemispheric coherence in general (see above) this result could be a hint for a specific way of information processing in dependence of tasks content (verbal versus nonverbal). This leads to the conclusion that possibly content specific cognitive processes are involved which in the concrete finding are reflected by differences in event related coherence.

Referring to the main effect of sexes' coherence and its underlying sexual dimorphisms in brain structure some conclusions regarding sex related intelligence differences in ERCoh may be drawn: As females show generally a lower neuronal density but more neuronal processes than men, females' information processing may be primarily reflected by efficient neuronal processes. This may give an anchor point for explaining sex related intelligence differences in EEG coherence (which is influenced by phase and power relationship of two signals): As bright women are able to activate the necessary and relevant cortex areas during task performance, consequently they are characterized by a lower overall functional coupling of different cortex areas and so display a low level of event related coherence. Lowly intelligent women however have an inefficient pattern of activation during task performance resulting in an overall unfocussed as well as higher activation level which as a consequent

effect causes a higher level of event related coherence compared to highly intelligent women. In contrast to females' brain structure, men are characterized by a higher neuronal density and a lower habitual activation (cf. Haynes and Moore, 1981; Burgess and Gruzelier, 1997). In case of men, information processing may be less reflected by efficient activation of cortical areas (neuronal processes) but more by activating efficient engramatic structures of the brain.

In contrast to activation level based EEG parameters (i.e. ERD), which proved to be relevant for indicating neural efficiency mainly in the upper alpha band (Neubauer et al., 1995, 1999, 2000a,b), event related coherence instead seems to be more relevant for the lower bandwidths (theta and lower-1 alpha). Taken together with the elaborations concerning anatomic brain structure dimorphism and its implications to sex and intelligence differences, it could tentatively be concluded that coherence indicates predominantly brains structural implications on IQ differences whereas ERD indicates mainly functional differences.

Finally it can be concluded that not only band-power or ERD but also EEG coherence parameters are of high importance to find and to develop a system of parameters indicating neural efficiency on the basis of physiological processes in the nervous system. Additionally the necessity of taking sex as factor together with bandwidth sensitive EEG methods into consideration was clearly demonstrated.

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Tables

Table 1

Descriptive statistics (mean and standard deviation) of event related coherence ERCoh, averaged over aggregated electrode pairs for interhemispheric long and short distance as well as for left and right sided intrahemispheric long and short distance scores during task performance (PRI interval) for each given frequency band and group.

		Groups	Sex												Content					
			Male						Female						Figural		Numerical		Verbal	
Frequency	Aggregated		IQ-Low		IQ-High		Total		IQ-Low		IQ-High		Total							
Band	electrode pairs		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Theta	Interhemispheric																			
	Long distance		0.14	0.04	0.25	0.04	0.20	0.03	0.34	0.04	0.17	0.04	0.25	0.03	0.20	0.02	0.23	0.02	0.24	0.03
	Short distance		0.40	0.05	0.54	0.06	0.47	0.04	0.62	0.05	0.43	0.06	0.53	0.04	0.46	0.03	0.51	0.03	0.52	0.03
	Right Intrahemispheric																			
	Long distance		0.27	0.05	0.40	0.06	0.34	0.04	0.53	0.05	0.30	0.06	0.42	0.04	0.36	0.03	0.38	0.03	0.39	0.03
	Short distance		0.31	0.02	0.31	0.02	0.31	0.01	0.29	0.02	0.29	0.02	0.29	0.01	0.31	0.01	0.29	0.01	0.30	0.01
	Left Intrahemispheric																			
	Long distance		0.28	0.05	0.42	0.06	0.35	0.04	0.51	0.05	0.33	0.06	0.42	0.04	0.37	0.03	0.39	0.03	0.38	0.03
Lower-1	Short distance		0.31	0.02	0.32	0.02	0.31	0.02	0.30	0.02	0.30	0.02	0.30	0.02	0.31	0.01	0.30	0.01	0.31	0.01
Alpha	Interhemispheric																			
	Long distance		0.10	0.03	0.14	0.04	0.12	0.03	0.26	0.03	0.12	0.04	0.19	0.03	0.14	0.02	0.16	0.02	0.17	0.02
	Short distance		0.35	0.04	0.40	0.05	0.37	0.03	0.55	0.04	0.38	0.05	0.46	0.03	0.40	0.02	0.43	0.02	0.43	0.03
	Right Intrahemispheric																			
	Long distance		0.24	0.05	0.28	0.05	0.26	0.03	0.45	0.05	0.28	0.05	0.37	0.03	0.30	0.03	0.32	0.02	0.32	0.03
	Short distance		0.31	0.02	0.32	0.02	0.31	0.01	0.28	0.02	0.27	0.02	0.28	0.01	0.31	0.01	0.29	0.01	0.28	0.01
	Left Intrahemispheric																			
	Long distance		0.24	0.04	0.30	0.04	0.27	0.03	0.44	0.04	0.28	0.04	0.36	0.03	0.31	0.02	0.32	0.02	0.32	0.03
Lower-2	Short distance		0.31	0.02	0.30	0.02	0.30	0.01	0.31	0.02	0.29	0.02	0.30	0.01	0.31	0.01	0.30	0.01	0.29	0.01
Alpha	Interhemispheric																			
	Long distance		0.08	0.02	0.10	0.03	0.09	0.02	0.17	0.02	0.08	0.03	0.12	0.02	0.10	0.01	0.11	0.01	0.11	0.01
	Short distance		0.28	0.03	0.31	0.04	0.30	0.03	0.45	0.03	0.32	0.04	0.38	0.03	0.33	0.02	0.35	0.02	0.35	0.02

	Right Intrahemispheric																
	Long distance	0.21	0.03	0.21	0.04	0.21	0.03	0.35	0.03	0.21	0.04	0.28	0.03	0.24	0.02	0.25	0.02	0.25	0.02
	Short distance	0.33	0.02	0.37	0.02	0.35	0.02	0.27	0.02	0.26	0.02	0.27	0.02	0.32	0.01	0.30	0.01	0.30	0.01
	Left Intrahemispheric																
	Long distance	0.20	0.03	0.23	0.03	0.22	0.02	0.33	0.03	0.24	0.03	0.29	0.02	0.25	0.02	0.25	0.02	0.25	0.02
Upper	Short distance	0.33	0.02	0.34	0.02	0.33	0.02	0.30	0.02	0.28	0.02	0.29	0.02	0.32	0.01	0.31	0.01	0.30	0.01
Alpha	Interhemispheric																
	Long distance	0.07	0.02	0.10	0.02	0.08	0.02	0.12	0.02	0.07	0.02	0.09	0.02	0.09	0.01	0.09	0.01	0.09	0.01
	Short distance	0.25	0.03	0.27	0.03	0.26	0.02	0.36	0.03	0.29	0.03	0.32	0.02	0.30	0.02	0.30	0.02	0.30	0.02
	Right Intrahemispheric																
	Long distance	0.18	0.03	0.20	0.03	0.19	0.02	0.28	0.03	0.18	0.03	0.23	0.02	0.21	0.02	0.21	0.01	0.21	0.02
	Short distance	0.32	0.02	0.35	0.03	0.34	0.02	0.24	0.02	0.25	0.03	0.25	0.02	0.30	0.01	0.29	0.01	0.29	0.01
	Left Intrahemispheric																
	Long distance	0.18	0.03	0.20	0.03	0.19	0.02	0.27	0.03	0.21	0.03	0.24	0.02	0.21	0.01	0.22	0.02	0.21	0.01
	Short distance	0.33	0.02	0.30	0.03	0.32	0.02	0.26	0.02	0.29	0.03	0.28	0.02	0.29	0.01	0.30	0.01	0.29	0.01

Note.
Coherence values are given in Fisher Z-transformation.

Table 2

Significant F-values for IQ group by sex by content ANOVAs over aggregated electrode pairs during task performance (PRI interval) for each given frequency band.

ANOVA Effect	IQ Group × Sex				Sex				Content			
		Alpha				Alpha				Alpha		
Aggregated electrode pairs / Frequency Band	Theta	Lower-1	Lower-2	Upper	Theta	Lower-1	Lower-2	Upper	Theta	Lower-1	Lower-2	Upper
Interhemispheric												
Long distance	10.55^{**}	7.43^{**}	5.94^{*}	4.27^{*}		4.11^{*}			5.08^{*}	4.15^{*}		
Short distance	10.12^{**}	6.14^{*}	4.48^{*}			3.68^{+}	5.76^{*}	4.85^{*}	5.75^{**}	4.70^{*}		
Right Intrahemispheric												
Long distance	10.31^{**}	5.04^{*}	3.64^{+}	4.72^{*}		5.08^{*}	3.77^{+}					
Short distance						3.96^{+}	13.20^{***}	13.83^{***}	2.64^{+}	9.48^{***}	5.43^{**}	
Left Intrahemispheric												
Long distance	9.56^{**}	6.59^{*}	4.08^{*}			4.02^{+}	4.44^{*}	3.38^{+}				
Short distance							3.81^{+}	2.83^{+}		4.24^{*}		

Note.

$^{+}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Figure caption

Figure 1: Schematic display of one matching test trial indicating the window for the Pre-Reaction-Interval (PRI) where event related coherence (ERCoh) calculation takes place.